Desalination 252 (2010) 179–185

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Operation of the RO Kinetic® energy recovery system: Description and real experiences ☆

B. Peñate [a,*], J.A. de la Fuente [a], M. Barreto [b,1]

[a] Water Department, Canary Islands Institute of Technology (ITC). Playa de Pozo Izquierdo s/n 35119 Santa Lucía - Las Palmas, Spain
[b] Polígono Costa Sur, calle 302, nave 6, 38009 Santa Cruz de Tenerife, Spain

ARTICLE INFO

Article history:
Received 14 October 2008
Accepted 27 June 2009
Available online 25 November 2009

Keywords:
RO Kinetic®
Energy recovery devices
Reverse osmosis
Energy consumption reduction
Continuous kinetic cycle

ABSTRACT

Along with the older style centrifugal energy recovery devices (ERDs), there has been a recent proliferation of ERDs that employ positive displacement mechanisms. These "pressure-equalising" or isobaric ERDs transfer the energy from the membrane reject stream directly to the membrane feed stream. This direct, positive displacement approach results in a net transfer efficiency up to 97% [R.L. Stover, Seawater reverse osmosis with isobaric energy recovery devices. Desalination, 203 (2007) 168–175]. A number of devices have been developed to recover pressure energy from the brine reject stream. These ERDs fall into two general categories: centrifugal and isobaric devices.

In order to avoid the efficiency losses associated with the energy-conversion steps inherent in centrifugal devices, in the 1980s engineers developed positive-displacement (PD) isobaric devices for seawater reverse osmosis (SWRO) plants. These devices place the SWRO reject and raw feed in contact in pressure-equalising or isobaric chambers. Current manufacturers of isobaric devices include Calder (DWEER™) [2], KSB (SalTec DT) [3], ERI® (PX) [4] and RO Kinetic® (RO Kinetic® is a patent of the Canary Islands engineer Manuel Barreto).

The RO Kinetic® is a novel energy savings system for RO desalination plants that implies an enormous advance in the specific energy consumption (SEC) reduction in this type of facilities. With this device, we are able to obtain a SEC of slightly higher than 2.20 kWh/m^3, which approaches the theoretical minimum limit for energy consumption in seawater reverse osmosis processes [5].

The physical principle that serves as the foundation for the RO Kinetic® system is the "incompressible property of liquids", making it possible to submit a mass of water to a given pressure without expending any energy. Pressure exchangers are used to put this principle into practice.

This article describes the state of the art of the RO Kinetic® energy recovery device; it explains the way it works and the advantages of using this type of ERD in SWRO plants. Furthermore it shows some operational data of different SWRO desalination plants with the RO Kinetic®.

© 2009 Elsevier B.V. All rights reserved.

1. RO Kinetic® description

Feed water accumulated in one of the pressure exchangers is pressurised with a high pressure pump (HPP). This step is accomplished by making a closed circuit between the membrane output and the reverse osmosis module input, where a water tank (pressure exchanger) and a booster pump are fitted into the line (Fig. 1).

The brine output from the RO rack and the SW input to the membranes are at the same static pressure, supplied by the HPP. The brine has to be fed into the pressure exchanger and displace the feed water contained in the chamber, forcing it into the module input. To achieve this, the pressure differential (ΔP) caused by pressure drops that take place in the membranes and in the pressure exchangers must be overcome. The pressure drop in the membranes is 1 to 2 bar. The pressure loss that occurs in the system during the circulation of

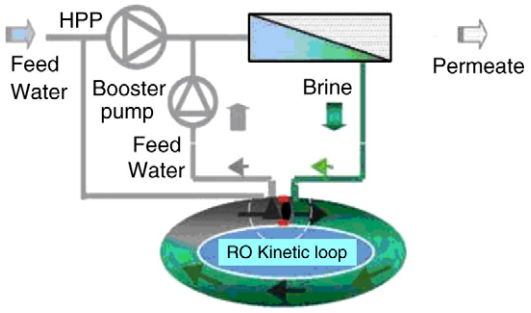

Fig. 1. Pressure exchanger making a closed circuit between the membrane output and the RO module input.

☆ This paper was peer reviewed under the editorship of Miriam Balaban.

* Corresponding author. Tel.: +34 928727511; fax: +34 928727590.
E-mail addresses: baltasarp@itccanarias.org (B. Peñate), barreto@step.es (M. Barreto).
[1] Tel.: +34 922230033; fax: +34 922214480.

0011-9164/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.desal.2009.06.078

Fig. 2. RO Kinetic® body of valves.
Source: Sisahen SLU.

Fig. 3. View of the RO Kinetic® body of valves. The flows inside are: 1. brine input in HP, 2. seawater output in HP, 3. seawater input in LP, 4. brine output in LP. (HP: high pressure, LP: low pressure).
Source: M. Barreto.

the seawater in the loops is also about 1 bar. Hence, the booster pump must overcome this pressure drop of about 3 bar [6].

The membranes will not only be fed by water from the high pressure pump, they are also fed with an amount of water that is equal to the volume of the reject but, in this case, pumped by the booster requiring only a minimum amount of energy.

The design houses all necessary valves (Fig. 2) and other mechanisms in a very small space. It consists of two bodies of servo-controlled valves, separated by two inertia valves. The banks of valves distribute input of seawater and output of brine from the pressure exchangers sequentially (Fig. 3). The design of these valves prevents cavitation, turbulence or and excessive pressure drops.

RO Kinetic® pressure exchangers are in the form of a ring or closed loop (Fig. 4) where the water entering or leaving them, which must be pressurized or depressurised, is always in continual motion to avoid unnecessary consumption of kinetic energy that arise from stops in the operation (Fig. 5). Furthermore, they are designed so that the ratio between length and diameter reduces the chances of excessive pressure drops or mixing.

The inertia valves are an extension to the pressure exchangers. The passage of the water from one chamber to another is done with practically no interruption, due to the speed with which valves are activated in order to maintain a continuous kinetic cycle.

In addition, the RO Kinetic® installation is equipped with an expansion bladder in order to act as a damper for the water shocks that may occur during the small stop that takes place during the valve operation while the chambers are filling up.

2. RO Kinetic® advantages

The main advantage is the *reduced specific energy consumption* achieved. The reverse osmosis process reaches levels of 2.10 kWh/m^3 (for a SWRO plant with a nominal production capacity of 2000 m^3/day), compared with 3.50 to 4.00 kWh/m^3 in optimised facilities using "conventional turbine-type" energy recovery devices. The reduction of the electrical consumption is between 25 and a 50% compared to plants with conventional ERDs. This reduction, of practically 50% of the variable costs in the desalination plant, represents a reduction of 25% of the total cost.

Maximum energy efficiency (approximately 98%). All of the reject pressure is harnessed to pressurise the seawater, without any of it being transformed into any other kind of energy. It is the only system in the world that takes maximum advantage of the kinetic energy, working in a continuous kinetic cycle [7] (between 8 and 10% of the energy is kinetic energy).

Absence of noise or vibrations that can end up causing failure from fatigue in the materials of the system, or in the materials of the rest of the plant [8]. The noise level produced by the RO Kinetic® can be considered negligible since it is masked by the booster pump and the HPP; it is estimated to be 10 dB for a few seconds when the change of valves takes place.

Reduced capacity of the high pressure pump. The HPP only needs to manage a flow equivalent to the permeate flow, reducing the operation volume by practically 60% of that necessary in conventional plants, leading to cost savings in the purchase of a smaller pump and electrical consumption.

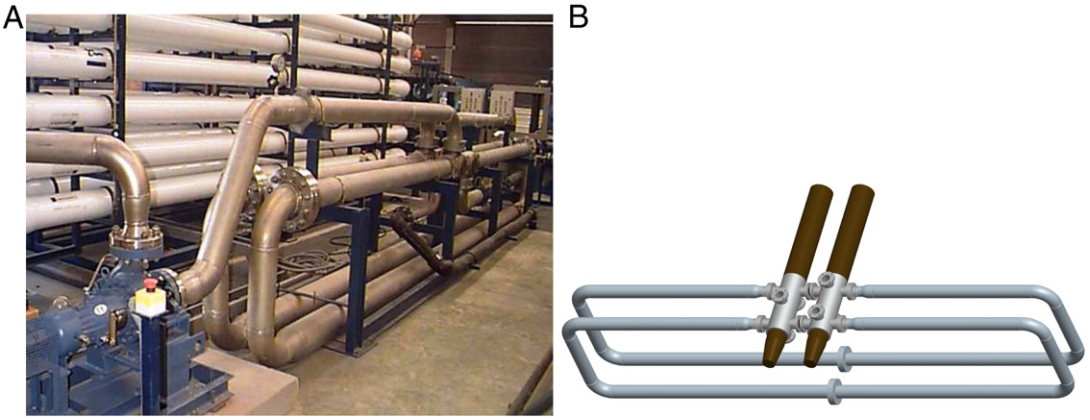

Fig. 4. RO Kinetic® loops.
Source: M. Barreto.

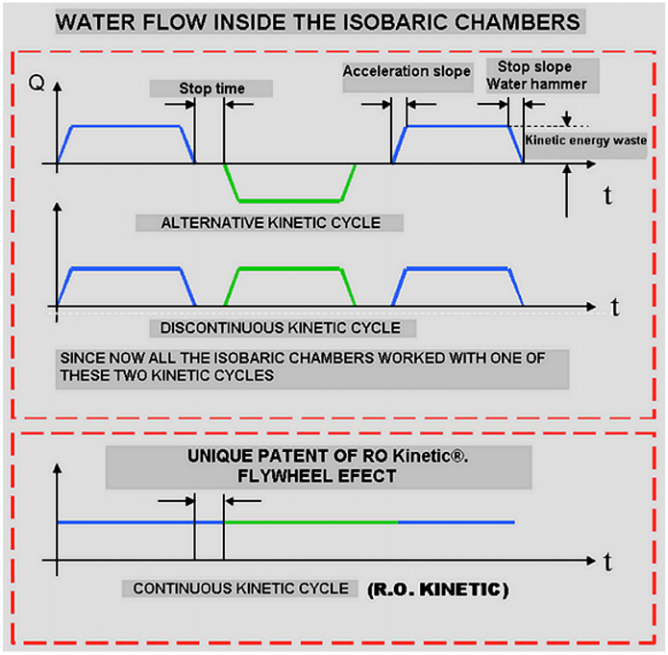

Fig. 5. Continuous kinetic cycle inside the isobaric chambers.
Source: M. Barreto.

Decrease in the amount of antiscalant needed. The recovery rate is reduced to 38% compared to 45% or higher in plants with conventional energy recovery systems. Due to this reduction, the reject flow increases causing a reduction of the brine concentration. This leads to better flow over the membrane surface, thus reducing scaling of the membrane and, consequently, reducing the quantity of antiscalant required, thus producing a noticeable saving in the production costs. The total cost of additives is approximately 0.02 €/m^3 compared to 0.05–0.06 €/m^3 for conventional reagents dosing rates; therefore the cost in reagents is reduced by 50% [8]. Working with a greater recovery rate increases the brine concentration, and the membrane flow is insufficient to remove the salts that deposit on the membrane surface. Increasing the recovery rate increases the pressure drop, thus increasing the HPP energy consumption. When working with isobaric chambers, the HPP contributes a flow equivalent to the permeate flow, the rest being contributed by the ERD by means of the booster pump, whose energy consumption is much lower than that of the HPP (8–10% of the HPP energy consumption). The optimal operation point of the RO Kinetic® is a recovery between 38 and 40%.

Low mixing percentage between seawater and brine in the isobaric chamber, which minimizes the increase of the total salinity and, thus, the increase of the pressure required in the process. This practically non-existent mixing happens because the liquid is always in movement inside the chamber; a moving mass of water never encounters a static mass, unlike what occurs with other isobaric ERDs. There is a mixing interphase of about 10 cm (it can be smaller according to the size of the loop), but the mixing is linear, it does not exist turbulence, reason why the mixing is not homogenous. In addition the valves are adjusted to make the change at the precise moment, avoiding an excessively prolonged contact between seawater and brine, therefore diminishing the mixing percentage between both currents.

Very slow operation (about 5 cycles per minute or less), which is translated into hardly any mechanical wear. This is unlike other high-speed rotating isobaric chamber ERDs that can suffer catastrophic failure if flow is exceeded. This almost maintenance-free operation constitutes a significant price reduction of the maintenance costs, apart from extending the system lifespan.

Very versatile installation with no need of great space requirements. The RO Kinetic® closed loops can be installed in very diverse ways (vertically, horizontally, under the reverse osmosis skid, in parallel to the skid or integrated into the skid structure).

The flexible water volume managed by each device reduces the number of units to install. This is achieved by dimensioning the volume of brine that can house the RO Kinetic® loops, and by regulating the timing of the pressure transitions with the valves adjusting.

The shutdown of a unit in parallel with several RO Kinetic® units does not cause a cascade shutdown of the rest of the units.

Unlimited capacity. Higher ERD capacity is achieved by operating multiple units in parallel.

3. Implementation possibilities

The RO Kinetic® energy saving system presents different possibilities of installation; therefore we will distinguish between already existing plants and new plants.

New plants: these plants benefit not only from the savings of specific energy consumption obtained with the incorporation of RO Kinetic®, but also from reduction in the cost of the high pressure pump, designed for the product water volume, which is only about 40% of the seawater managed by the plant.

Already existing plants: There are two possibilities.

1. To maintain the plant production and reduce the specific energy consumption of the installation up to 50% in many plants, hence diminishing operational costs. It is only necessary to incorporate a VFD (variable frequency drive) to the high pressure pump to regulate its operating frequency, since the new flow is reduced to 40% of the nominal flow.
2. To maintain the present plant energy consumption and increase the plant production. The present flow of the high pressure pump becomes the permeate flow; therefore incorporating the necessary pressure vessels we have obtained an increase of flow between 2 and 2.5 times the initial plant flow. Thus, we are able to reduce the plant's specific energy consumption since we have increased the production whilst maintaining the same electrical consumption.

4. Parameters evaluated in the selection of the energy recovery device

4.1. Recovery and flux variation

Recovery and flux variations can occur naturally as the temperature and salinity of seawater changes and aging of the SWRO system components begins. Their design, however, is optimised for a particular operating window. The degree to which centrifugal ERD performance varies as a function of recovery and membrane flux changes depending upon the characteristics of a particular device and must be considered in the SWRO design process. Isobaric ERDs deliver more constant performance with little efficiency variation over their operating range, but the flow variation may be limited by device capacity. In addition, an isobaric ERD recovery can be altered without directly changing HPP operation. This is a distinct advantage of operating a SWRO system with these type of devices.

Isobaric ERDs allow the SWRO system operator to vary membrane flux and recovery independently. If the flow rate of the booster pump is set with a variable frequency drive to be equal to the flow rate of the HPP, the system will operate at 50% recovery. If the flow rate of the booster pump is increased to double the flow rate of the HPP, the system will operate at 33% recovery. Neither of these operations significantly changes the HPP flow rate nor the permeate flow rate. Membrane flux can also be adjusted independent of recovery, although less easily, by directly manipulating the HPP or permeate flow or pressure using a control valve, a variable frequency drive or an adjustable supply-booster pump. The decoupling of HPP operation and ERD and booster-pump operation provides significant design and operational flexibility.

Table 1

SWRO desalination plant	El Fraile	El Confital	Arona Hotel	Aguas de Ponta Preta		Aguas de Porto Novo	Lanzarote airport (dismantled)
Start up year	2002	2004	2007	2001 (rack 1); 2004 (rack 2)	2007 (rack 3)	2007	2002 (2006)
Nominal production capacity (m^3/d)	1800	4000	200	500 + 500	1000	500	350
Conversion rate (%)	38	38	28	40.25	31.40	40	39
Type of RO Kinetic® installed (units)	K-1000 (1)	K-1000 (2)	K-200 (1)	K-200 (2)	K-1000 (1)	K-200 (2)	K-200 (1)
Nominal working pressure (bar)	57	NA	51.50	64	64–68	36	50
Specific energy consumption (kWh/m^3)	2.25	2.13	2.10	2.39	2.95–3.34	1.22[a]	2.21

NA. Not available.
[a] See Porto Novo desalination plant explanation.

With the RO Kinetic® ERD the best operation point, where we obtain the lowest SEC, is operating with a recovery rate around 38–40% [9].

4.2. Ease of operation

The piston isobaric device requires direct operational control. Centrifugal ERDs and the non piston isobaric devices are flow-driven and self-adjusting. An advantage offered by the isobaric devices over centrifugal devices is fail-safe operation and redundancy. In medium and large SWRO trains where several isobaric devices are arrayed in parallel, the loss of one unit due to debris or damage has minimal impact on the SWRO membrane performance. As there are no intervening pistons, flow passes through the device and a plant can typically continue running until scheduled maintenance solves the problem. Failure of any other type of ERD typically involves shutdown of the SWRO train.

The operation point regulation is less complicated in the RO Kinetic® system since it has the possibility of regulating the timing of the pressure transitions by means of the management of the variable frequency drive of the system levies.

4.3. Maintenance

ERD maintenance must be considered in SWRO system operation because of the direct costs and the associated system downtime. Centrifugal ERDs and the rotary isobaric device require no periodic maintenance. Piston isobaric ERDs require periodic maintenance of the piston and all the valves and subsystems necessary for device operation. The RO Kinetic® device needs minimal maintenance mainly due to its slow operation regime [8].

4.4. Device life

Factors that adversely affect the longevity of SWRO equipment include corrosion, vibration and abrasion (specifically, valve wear manifests as excessive leakage and piston wear as excessive mixing). ERDs are typically made with high-quality stainless steel alloys which offer resilience against damage by debris and corrosion (the RO Kinetic® loop could be made with Super Duplex stainless steel, even more corrosion-resistant than other usual steels). Pulsations produced by piston isobaric ERDs have been known to damage SWRO equipment. Pressure transfer in the RO Kinetic® device occurs in a closed loop with no piston involved so vibrations and pulsations are negligible [7]. This is also due to a very slow operation (about 5 cycles per minute or less), which is translated into hardly any mechanical wear. In addition, the RO Kinetic® installation is equipped with an expansion bladder in order to act as a damper for the water shocks that may occur during the small stop that takes place during the valve operation.

4.5. Mixing

Mixing requires measurement of seawater contamination by the brine. In all commercially available isobaric ERDs, some contact between the brine and seawater streams occurs inside the device. As a result, these streams mix slightly. The ratio of the volume of brine that transfers into the seawater to the flow rate of the seawater, known as volumetric mixing, can be calculated with the following equation:

$$M = \frac{(S_{HPout} - S_{FW})}{(S_{HPin} - S_{FW})}$$

where M is the volumetric mixing, SHPout is the salinity of the high-pressure water leaving the ERD, SFW is the salinity of the system feed water, and SHPin is the salinity of the high-pressure brine [1].

Volumetric mixing is a function of the mixing characteristics of the specific ERD and the ratio of seawater and brine fed to the device but is independent of the membrane recovery rate. Mixing increases

Fig. 6. RO Kinetic® K-1000, 1,800 m^3/d in El Fraile SWRO plant. Source: M. Barreto.

Fig. 7. RO Kinetic® K-1000, 4,000 m^3/d in El Confital SWRO plant. Source: M. Barreto.

Fig. 8. Two membrane skids with their RO Kinetic®.
Source: M. Barreto.

Fig. 10. RO Kinetic® K-200, 500 m^3/d Ponta Preta SWRO plant.
Source: M. Barreto.

the membrane feed salinity to slightly above the salinity of the system feed.

In the RO Kinetic® ERD there is practically non-existent mixing because inside the chambers the liquid is always in movement and in the same direction; a volume of water never impacts on another one at rest.

4.6. Overflushing

Overflushing is the seawater volume that is lost with the brine exit. In a piston-type isobaric ERD, it happens during the chambers transition from high to low pressure as the piston contained in the chamber moves back and forth. A control system is used to manipulate valves and coordinate the timing of the pressure transitions and the piston movement in each chamber with that in the other chambers. Each cycle of the piston can be thought of as a batch process. The control system coordinates these batch processes to accommodate the continuous flow of brine from the membranes. Often times, water must be bypassed or dumped during each cycle to maintain coordination between all the chambers in an array. This loss of pumped and treated water is called overflush. The RO Kinetic® ERD operates automatically and continuously with no overflush.

4.7. Leakage

Leakage is the brine flow that is lost before the exchange, giving rise to an efficiency loss. These brine losses take place directly from the high pressure side to the low pressure one. Measured in absolute flow values, it corresponds with the brine flow entering the chambers, minus the brine flow leaving the chambers.

4.8. Efficiency

The performance of a pressure exchanger is measured by the efficiency of the energy transfer process and by the degree of mixing between the streams. The energy of the streams is the product of their flow rates and pressures. Efficiency is a function of the pressure differentials and the volumetric losses (leakage) through the device computed according to the following equation:

$$\eta = \frac{\Sigma \text{energy out}}{\Sigma \text{energy in}} = \frac{(Q_G - L) \times (P_G - HDP) + (Q_B + L) \times (P_B - LDP)}{Q_G \times P_G + Q_B \times P_B}$$

where Q is flow, P is pressure, L is leakage flow, HDP is high pressure differential, LDP is low pressure differential, the subscript B refers to the low pressure feed to the device and the subscript G refers to the high pressure feed to the device [1].

As we have mentioned before, the RO Kinetic® ERD has maximum energy efficiency (close to 98%) since all of the reject pressure is harnessed to pressurise sea water, without any of it being transformed into any other kind of energy. Moreover, it is the only system in the world that takes maximum advantage of the kinetic energy, working in a continuous kinetic cycle.

5. RO Kinetic® operation and full-scale plant experience

There are several medium RO desalination plants installed with the RO Kinetic® energy recovery device. Some of these real experiences are described in the following pages. In Table 1 below you can find the operation data of the RO facilities.

Fig. 9. RO Kinetic® K-200, 200 m^3/d in Arona Hotel SWRO plant.
Source: M. Barreto.

Fig. 11. RO Kinetic® K-1000, 1000 m^3/d Ponta Preta SWRO plant.
Source: APP.

Fig. 12. General view of the Porto Novo SWRO plant.
Source: APP.

Fig. 14. RO Kinetic® K-200, 350 m^3/d in Lanzarote airport SWRO plant.
Source: M. Barreto.

El Fraile SWRO desalination plant (Fig. 6) located in the town of Arona in the south of Tenerife (Canary Islands).

El Confital SWRO desalination plant located in the town of Granadilla de Abona in the south of Tenerife (Canary Islands) (Figs. 7 and 8).

Arona Hotel SWRO desalination plant in Los Cristianos in the south of Tenerife (Canary Islands) (Fig. 9).

There are two more SWRO plants with a RO Kinetic® ERDs installed in the islands of Sal in 2001 (owned by Aguas de Ponta Preta, Figs. 10 and 11) and Santo Antão in 2007 (owned by Aguas de Porto Novo, Figs. 12 and 13) in Cape Verde.

The island of Sal's subsoil is formed by basaltic rock whose pores are impregnated with salt crystals which increase the seawater salinity (the conductivity of the feed water is 64.90 mS/cm).

In the third membrane skid, the latest generation RO Kinetic® was installed; it incorporates linear mechanical actuators for the pistons movement instead of the traditional gear motor. The earlier prototypes suffered internal water leaks in the valves that caused an increase in salinity that produced a pressure rise between 64 and 68 bar.

The Porto Novo SWRO plant seawater intake consists of beach wells that are affected by underground intrusion of fresh water runoff coming from underground river basins in the Island of Santo Antão, which allow very low nominal working pressures, with a seawater conductivity of approximately 33 mS/cm.

The Lanzarote airport (Canary Islands) has a SWRO plant with a RO Kinetic® K-200 installed (Figs. 14). Nowadays, this plant is no longer in operation.

Fig. 13. View of the RO Kinetic® K-200, 500 m^3/d.
Source: APP.

6. Conclusions

Energy recovery devices have become essential to all SWRO operations, primarily because they significantly reduce energy consumption in these systems. Quantifying device performance involves employing relatively straight-forward hydraulic calculations. ERD selection, like all other aspects of engineering design, involves some degree of compromise. Isobaric ERDs deliver higher efficiency than centrifugal devices, but centrifugal devices are generally better characterised and are easier to maintain and operate. The RO Kinetic® energy recovery device provides high energy transfer efficiency, practically no maintenance, great ease of operation.

In the early days of seawater desalination, the energy consumption was about 20 kWh/m^3 [8]. The yields improvements in the plants components (especially in the membranes), made possible to reduce gradually the specific energy consumption of the process, that with systems like RO Kinetic® reaches values around 2.20 kWh/m^3. From experience gained in full-scale plants we can conclude that we have an energy recovery device able to reduce considerably the specific energy consumption and therefore the operational costs, approaching the minimum theoretical limits in the energy consumption values of reverse osmosis seawater desalination process. The system adaptability allows a very versatile installation, being able to locate the RO Kinetic® closed loops in very diverse configurations. The device valves are concentrated occupying a reduced space. These advantages are also transferred to the fact that they do not affect to other facility components such as membranes, valves, pipes, etc. Due to its extremely slow operating regime, it becomes a reliable device with very simple maintenance. Since 2002, once surpassed the initial experiences, RO Kinetic® becomes a technology accessible to any operator or manufacturer of this type of facilities. The attainable values of specific energy consumption with the RO Kinetic® system are close to the theoretical minimums, investigation in the future should concentrate on other aspects of desalination.

Acknowledgements

The authors wish to acknowledge the FEDER and Canarian funds for their support in the project; we also want to acknowledge to Miguel A. Fernandez from TESA and Jose L. Libreros, Damià Pujol and Cristian Bicarelli from Aguas de Ponta Preta in Cape Verde for providing thorough data of the operation of their plants and their experience. Finally our acknowledgement to the engineer Walter Wesson for his contribution in the correct language usage in this paper.

References

[1] R.L. Stover, Seawater reverse osmosis with isobaric energy recovery devices, Desalination 203 (2007) 168–175.
[2] B. Schneider, Selection, operation and control of a work exchanger energy recovery system based on the Singapore Project, Desalination 184 (2005) 1177–1190.
[3] S. Bross, SWRO core hydraulic system: extension of the SalTec DT to higher flows and lower energy consumption, Desalination 203 (2007) 160–167.
[4] R.L. Stover, The Ghalilah SWRO plant: an overview of the solutions adopted to minimize energy consumption, Desalination 184 (2005) 217–221.
[5] J.M. Veza, Introducción a la desalación de aguas, ULPGC publicaciones, 2002.
[6] J.P. Plasencia, Energy-saving RO system taps Kinetic forces, Water & Wastewater International, June 2004.
[7] Dpto. Técnico Tecnovalia, Sistema de ahorro de energía R.O. Kinetic, Infoenviro (Junio 2006).
[8] J.P. Plasencia, R.O. KINETIC: El Sistema de Ahorro de Energía, Presented at AEDyR Conference, Málaga, 2002.
[9] J.M. Sánchez Alonso, Tecnología Canaria del Agua S.A., Sistemas de ahorro energético: comparativa de implantación de dos sistemas de ahorro energético en unidades de desalinización de agua de mar destinadas a uso agrícola. Presented at AEDyR Conference, Málaga, 2002.